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Thermohydraulic simulation of a channel with targets for production of radioactive isotopes in the IVV-2M nuclear reactor

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Abstract. The importance of radioisotope products usage in industry, science and medicine is underlined. The necessity of safety ensuring and radiation protection optimization while transporting the containers with radioactive isotopes is postulated. The information on isotope products making in the IVV-2M nuclear reactor of Research Institute of Nuclear Materials, JSC, from the beginning of 1990-ies is given. The data on application properties of Selenium 75 isotope are presented. The requirements to the thermohydraulic conditions of Se 75 isotope production in the nuclear reactor are formulated. The stages of a solid model development of a target for Se-75 isotope production as a part of an irradiation device of IVV-2M nuclear reactor are described. The results of hydraulic simulation of the coolant flow for various ways of devices arranging in the irradiation channel of the reactor are given. The analysis of thermohydraulic processes was performed with the help of SolidWorks Flow Simulation software.

1. Introduction

The role of radioisotopes is constantly growing as technical progress develops. The isotopes are produced in nuclear reactors and elementary particle accelerators. The reactor method of production includes placing the capsule with target isotope in the reactor core, where needed isotopes are generated under the impact of neutron radiation [1], [2]. Transport of radioactive isotopes to the consumer is performed in special protective containers. The safety of transport is ensured by radiation protection depending on the radiation type (β -, γ -) and its energy [3], [4]. The optimization of radiation protection materials composition significantly influences the economic indicators of the isotope products transportation to the consumer [5], [6], [7].

In 1960-ies – 1980-ies a thermal neutron research nuclear reactor IVV-2M of the Research Institute of Nuclear Materials, JSC, situated in Zarechniy town, was used to carry out scientific research in the sphere of radiation material study, to test fuel compositions and parts of nuclear reactors' cores and to perform other tasks. In 1990-ies INM JSC started production of radioisotopes. Today it successfully combines research work and radioisotope products making. The production of radioactive isotopes exploits more than two thirds of IVV-2M reactor resources [8].



Selenium-75 is one of the most needed isotopes which is used as a source of gamma-radiation in defectoscopy [9] and medicine. This radioisotope is produced by irradiation of natural isotope of selenium-74 with neutrons. Selenium-75 is an alternative to iridium-192, having longer half-life. It provides softer spectrum of gamma-radiation, therefore the radiographic monitoring sensitivity increases. Selenium-75 decays as a result of electron capture with half-life of 120 days.

The aim of the current work is thermohydraulic analysis of operation of an irradiation device for selenium-75 radioactive isotope production in the IVV-2M research reactor using computational fluid dynamics methods.

The peculiarities of the reactor design and nuclear processes in it make it difficult to carry out an experimental investigation of heat exchange and hydrodynamic characteristics of the irradiation device for isotope production. That is why SolidWorks Flow Simulation was applied to perform thermohydraulic simulation of a channel with targets for selenium-75 production.

The authors have earlier conducted thermohydraulic simulation and analysis of the conditions of selenium-75 isotope production in the target which was situated in the irradiation channel of IVV-2M nuclear reactor [10], [11]. The plots of temperature distribution in the construction materials and the coolant as well as fields of velocity and pressure were obtained as a result of simulation.

2. Materials and Methods

The summary report of a technical meeting jointly organized by the International Atomic Energy Agency and the Nuclear Energy Agency [12] became a starting point of intensification of the use of CFD methods in the sphere of atomic energy. From this point, IAEA carries out complex work on the CFD-simulation in atomic energy promotion.

The department of Nuclear power plants and renewable energy sources of Ural Federal University carries out the research work on thermohydraulic simulation of processes in the systems and equipment of nuclear power facilities since the year two thousand. Some results of this work are presented in [13], [14], [15].

Current work applies SolidWorks Flow Simulation software for thermohydraulic processes simulation. According to multiple studies and verification performed, the results of convective heat exchange simulation with Flow Simulation show good coincidence with the data of experiments and highly tailored computation codes in case of phase change absence [16].

SolidWorks Flow Simulation uses laws of mass, angular momentum and energy conservation in the form of Favre-averaged Navier-Stokes equations as governing equations of mathematical model of gas or liquid motion and heat exchange [16]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial t}(\rho u_i) = 0 \quad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i u_j) + \frac{\partial p}{\partial x_i} = \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{ij}^R) + S_i, \quad i = 1, 2, 3 \quad (2)$$

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i}(u_j(\tau_{ij} + \tau_{ij}^R) + q_i) + \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho \varepsilon + S_i u_i + Q_H, \quad (3)$$

where u is the fluid velocity; ρ is its density; S_i is the mass-distributed external force (gravity, forces of rotation or porous medium resistance); $H = h + u^2/2$; h is enthalpy; Q_H is the heat source per unit volume; τ_{ij} is viscous stress tensor, τ_{ij}^R is Reynolds viscous stress tensor, q_i is diffusive heat flux. Indices indicate the summation in three coordinate directions.

A two-equation turbulence k - ε model is used to determine turbulent eddy viscosity and kinetic energy of turbulent pulsation, which are present in the equation of the viscous shear stress tensor and Reynolds-stress tensor [16]. Here k is turbulent kinetic energy, ε is dissipation. The equations are supplemented with the dependencies of viscosity, density, heat capacity and thermal conductivity on the temperature. Numerical solution of the equations is performed on the orthogonal computational

mesh, which is refined in the regions of small solid/fluid interface or high gradients of calculated parameters. This approach allows perform simulation for solid models of complicated geometry [16].

In order to achieve the simulation aim the authors set the following tasks:

- Creation of a solid model of a channel with targets for isotope production;
- Computer simulation problem definition in SolidWorks Flow Simulation and calculation verification;
- Calculation for several modes and result analysis.

The solid model of the device for isotope production is shown in the Figure 1. Each model consists of ten aluminum tubes in which the capsules with target material selenium-74 are placed. The tubes are mounted in the steel retainer and covered with a perforated cover.

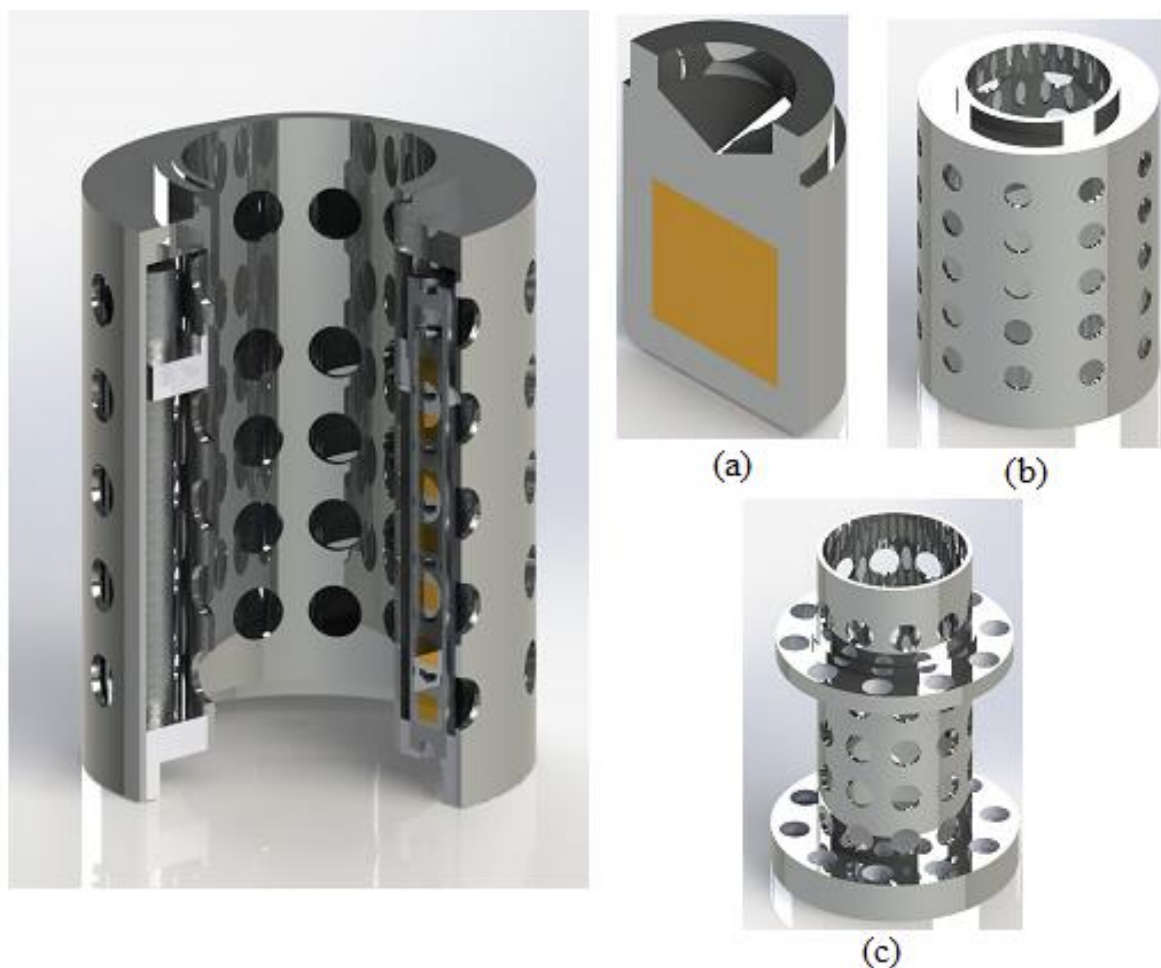


Figure 1. An assembled irradiation device with mounted targets for selenium-75 isotope production and its elements: a) a vanadium cell with metallic selenium, b) cover, c) steel retainer.

The targets (irradiation devices) for isotope production are arranged in the nuclear reactor in special cells (channels), which are situated between the fuel assemblies. A model of a channel in the form of a hexahedral case was created to perform the analysis in Flow Simulation, where several irradiation devices models were put sequentially and the coolant flow was organized. The influence of the surrounding fuel assemblies was simulated with boundary conditions. The calculation was made for the inner problem with coolant moving through the channel with three, five, seven or nine irradiation

devices. The flow velocity at the channel inlet and the environmental pressure at the channel outlet were set. Radiation capture in the target material causes heat release, but it is not taken into consideration because this heat is negligible in comparison with heat release of fuel assemblies.

3. Results and discussion

The fields of velocity of coolant flow for various number of irradiation devices in the channel and number of cells with target material in the device were achieved as a result of simulation of thermohydraulic modes of selenium-75 isotope production from selenium-74 target isotope. Figure 2 shows the velocity fields for the channel with three, five, seven or nine irradiation devices (targets).

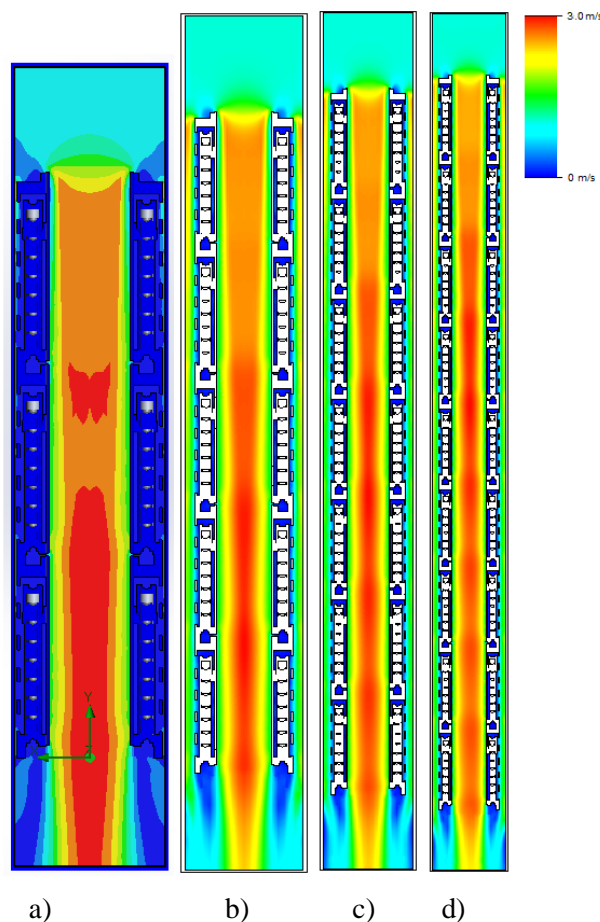


Figure 2. Distribution of coolant flow velocity in the targets for a) three, b) five, c) seven and d) nine irradiation devices, arranged sequentially in the channel (the plots are given in different scale).

The coolant flow moves downwards in the channel with irradiation devices. The velocity cut plots show that in the inner space of the irradiation device flow velocity is low. Main flow goes through the cylindrical cavity in the irradiation device center and in the gap between the irradiation devices and channel case walls. The picture observed at the inlet of the irradiation device row corresponds to the flow diagram in case of sudden contraction of a channel, namely vortex structures are formed in the frontal part of the first irradiation device. The stream contracts after entering the narrower part and then becomes wider up to the full section of the narrower channel. At the outlet of the irradiation device row we observe flow expansion. A region of lower pressure is formed in the rear part of the last irradiation device, where vortices are generated. These vortices are periodically torn off and carried away by the flow, as it occurs with flow around any blunt body. Thus, at a first approximation the irradiation devices in the channel can be considered as annular obstructing elements without consideration of perforation in them.

For the flow in the central channel of the irradiation device row it is observed the increase of the velocity of the flow core near the joints between the irradiation devices. Figure 2, a, shows that the velocity leap is present in the flow core at the region of the first and the second irradiation devices joint. Similar increase of velocity can be noticed in the region of the second and the third devices joint. In case of greater amount of irradiation devices the increase of velocity in the flow core is also observed near the joints, and the velocity leap for the first and the second joints is less noticeable than for the subsequent joints. Probably, such leaps are connected with pressure loss of overcoming of local obstacles of joints. The flow is separated from the wall in the region of joint of irradiation device, vortex structures are formed, that is why the flow section becomes narrower. Then the flow expands again up to full section of the channel – till the next joint.

Thus, at a first approximation the coolant flow through the row of irradiation devices can be described as a flow in a channel consisting of outer annular part and inner circular part with periodic roughness.

Figure 3 shows the dependence of cross-section average pressure on the vertical position in the channel. The pressure was measured in cross-sections corresponding to the joints between the irradiation devices. The diagram shows the relative pressure, which was determined as

$$\bar{p} = \frac{p_i - p_0}{\Delta p}, \quad (4)$$

where p_i is pressure in i -th cross section, p_0 is pressure at the first irradiation device inlet, Δp is pressure drop between the inlet and outlet of the row of irradiation devices.

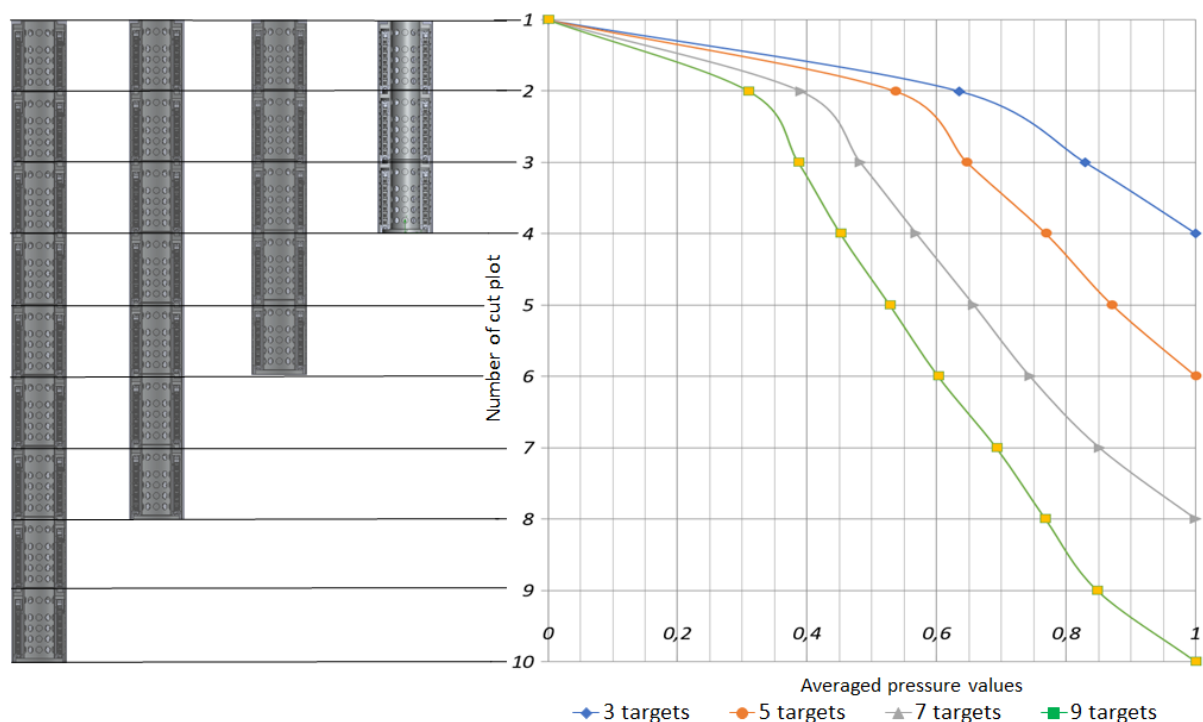


Figure 3. Distribution of pressure in the channel for various number of targets along the channel height.

The pressure distribution shows that the maximum pressure drop is observed in the first irradiation device. It is connected with the presence of sudden contraction losses. Further fall of pressure is more or less uniform. Next sudden change is observed at the channel outlet, it is probably connected with the expansion loss.

4. Conclusion

Computer simulation of different modes of coolant flow in the irradiation channel of the IVV-2M nuclear reactor with irradiation devices containing target material selenium-75 with SolidWorks Flow Simulation allows estimate needed flow rates and velocities in order to keep proper temperature conditions for selenium-75 production. It also allows determine optimum amount of targets and capsules with target material in the channel and reveal the geometry defects and eliminate them. In the sequel, after the target model optimization, it is planned to carry out experimental investigation of the flow modes in the irradiation channel of the IVV-2M reactor.

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